Pre-Stack Seismic Inversion and Amplitude Variation with Offset (AVO) Attributes as Hydrocarbon Indicators in Carbonate Rocks: A Case Study from the Illinois Basin

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PRE-STACK INVERSION AND AMPLITUDE VARIATION WITH OFFSET (AVO) ATTRIBUTES AS HYDROCARBON INDICATORS IN CARBONATE ROCKS: A CASE STUDY FROM THE ILLINOIS BASIN

A Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science

by

JACOB T. MURCHEK
B.S. Purdue University, 2018

2021
Wright State University
I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION
BY Jacob T. Murchek ENTITLED Pre-Stack Seismic Inversion and Amplitude Variation with
Offset (AVO) Attributes as Hydrocarbon Indicators in Carbonate Rocks: A Case Study from the
Illinois Basin BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR
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ABSTRACT

Murchek, Jacob T., M.S, Department of Earth and Environmental Sciences, Wright State University, 2021. Pre-Stack Inversion and Amplitude Variation with Offset (AVO) Attributes as Hydrocarbon Indicators in Carbonate Rocks: A Case Study from the Illinois Basin

Amplitude anomalies in pre-stack seismic data have widely been used in the oil and gas industry as a risk analysis tool when exploring for hydrocarbons. AVO analysis is most often applied to poorly consolidated Tertiary rocks due to the compressibility of these strata when natural gas and porosity are present. In contrast, well-lithified carbonate rocks are less prone to producing a pre-stack amplitude response due to the rigidity of their frame.

Pre-stack seismic data of a 2-D seismic profile were conditioned and interpreted to identify amplitude variation with offset (AVO) attributes corresponding to the presence of hydrocarbons within the North Vernon Limestone (NVL) interval in the Illinois Basin. The seismic data were acquired over the Glen Ayr oil field in Vigo County, Indiana, and in the Old Hill oil field in Clay County, Indiana prior to wells being drilled. Production in both fields is from porous dolomites draped by tight limestone or dolomites over a Silurian reef complex.
We show that with appropriate pre-stack data conditioning subtle AVO responses in Illinois Basin carbonates may indicate the presence of hydrocarbons. Seismic line CM-46-12 (Clay) and CM-27-14 (Vigo) were both analyzed using AVO attributes to identify anomalous zones that may relate to the presence of hydrocarbons.

Seismic Line CM-27-14 was further interpreted using pre-stack inversion to provide additional information pertaining to the reservoir rock properties. The results on both seismic lines show strong, negative AVO gradients along the NVL interval, whereas nonproductive intervals exhibit either positive or no amplitude gradient. Pre-stack inversion of lime CM-27-14 shows high impedance zones which are consistent with the presence of tight dolomite atop the reef structure. Low-impedance, low VP/VS ratio zones correlate to the hydrocarbon bearing porosity zones of the NVL interval.
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Dedicated to my late parents, Thomas, and Terri Murcheck,

without whom I would not be the person I am today.
I. INTRODUCTION

I.1 Overview

Seismic data donated by CountryMark were conditioned and interpreted to locate hydrocarbon-bearing zones along the North Vernon Limestone (NVL) interval in the eastern Illinois Basin (Figure 1). Two seismic reflection lines over separate oil fields were analyzed to compare the usefulness of amplitude versus offset (AVO) analysis in carbonate rocks. The seismic lines, CM-27-14, and CM-46-12 were chosen in localities where well control verified the absence or presence of hydrocarbons within the NVL interval. CM-46-12 was collected in Clay County, Indiana in Old Hill oil field (Figure 2). CM-27-14 was collected in Vigo Country, Indiana in Glenn Ayr oil field (Figure 3). The lines were shot prior to drilling and interpreted based on the pre-stack methods mentioned above.

Figure 1: Approximate extent of Illinois Basin (blue), along with Vigo (green) and Clay (red) counties where the seismic lines were shot.
Figure 2: Location of seismic line (red) CM-46-12 in Clay County Indiana. Modified using Indiana base map. The figure shows the wells analyzed in this study labeled A-E along with if they were dry, producers, injection, or dry holes.

Figure 3: Location of seismic line CM-27-14 in Vigo County, Indiana. Modified using Indiana base map. The figure shows the wells analyzed in this study labeled A-E along with if they were dry, producers, injection, or dry holes. The dots represent the deviation of wells.
I.II Geologic and Production Background

The Illinois Basin is known for its historical hydrocarbon production. Oil was first discovered in the Illinois Basin in 1886, but the basin did not become an important producer until 1905 when shallow oil fields were discovered in Pennsylvanian to Ordovician rocks (Mylius, 1927). However, it was not until 1946 that production from Silurian reef complexes was initiated (Prezbindowski, 2016). Glen Ayr and Old Hill fields, like other Silurian reef fields in the central and eastern Illinois Basin, exhibit a Silurian aged reef overlain by Devonian aged limestone and New Albany Shale (NAS) with the reservoir developed in the Devonian limestone (Figure 4). These stratigraphic zones are outlined in Figure 5 with a stratigraphic column obtained from the Indiana Geological and Water Survey (IGWS). The thin interval between the NAS and the limestone allowed for the downward migration of oil into these reef-drapped reservoirs. Thus, the NAS is a source rock for these reservoirs and acts as a seal unless underlain by non-porous limestone (Macke, 1995).

The wells in both Glen Ayr and Old Hill oil fields were drilled primarily based on the structural highs associated with the drape over the reef. However, structural traps (i.e. faults down-dip) within the reef-based complexes may trap hydrocarbons in areas away from the structural high. Approximately 2 percent (roughly 130 MMBO) of the recoverable oil discovered in the Illinois Basin has been found in Silurian reefs, or in drape structures over these features in both southwestern and eastern Illinois and in reefs on the northern shelf of the basin (Macke, 1995). With the use of advanced seismic methods, economic reservoirs may still be identified within these reef complexes, as well as in deeper plays throughout the Illinois Basin.
Figure 4: Typical structure of a reef-drape trap in the northern Illinois Basin. The Devonian limestone forms a drape over the reef and the Silurian limestone and dolomitic beds. From Bristol, 1974, modified by Lindell Bridges (personal communication).

Figure 5: A simple stratigraphic column showing formations of interest, from Indiana Geological Survey.
I.III Pre-Stack Interpretation

The purpose of this study is to use pre-stack seismic data interpretation to identify hydrocarbon bearing zones within the Glen Ayr and Old Hill oil fields, constrained and confirmed by well data. Pre-stack seismic data contains valuable information pertaining to the seismic rock properties related to reflected amplitudes. However, the stacking process diminishes the offset-dependent response generated by the rock properties and pore fluids present. Therefore, pre-stack amplitude anomalies may suggest the presence of hydrocarbon-filled porosity, in contrast with stacked data. Figure 6 shows the stacked seismic response from line CM-46-12, and Figure 7 represents the stacked section from CM-27-14. The post-stack data shows little indication of amplitude variation along the NVL interval (outlined in black).

Amplitude variation with offset (AVO) refers to the change in reflected wave amplitude with increasing offset. The four classes of AVO responses typically observed are shown in Figure 8. AVO attributes, such as intercept and gradient (slope), reduce AVO information into a more readily interpretable form (Chopra and Castagna, 2014), which directly relate to the seismic rock properties. Utilizing pre-stack data as an exploration tool reduces risk instead of drilling entirely based on structure. In this study, we demonstrate how pre-stack data can be used even in carbonate rocks to identify prospects using AVO analysis.
Figure 6: Stacked seismic section from line CM-46-12. The 5 wells used in the study are depicted. There is no amplitude variation present along NVL interval (outlined in black).

Figure 7: Stacked seismic section from line CM-27-14. The 5 wells used in the study are depicted. There is no amplitude variation present along NVL interval (outlined in black).
Both $V_P$ and $V_S$ are affected by the shear modulus and bulk density. However, the p-wave velocity (Eq. 1.1) has the additional component of the bulk modulus (incompressibility) which is sensitive to pore fluid content; the shear modulus is not. Therefore, changes in $V_P$ relative to $V_S$ can be attributed to changes in pore fluid content caused by the presence of natural gas. AVO responses are often observed in gas-filled, poorly consolidated “soft” rocks due to the weak frame modulus and the presence of gas; both of which decrease the bulk modulus resulting in a lower Poisson’s ratio. The lower Poisson’s ratio causes a sharp reduction in $V_P$, and an unchanged $V_S$.

Figure 8: Describes the 4 sand classes of AVO responses. Modified from Castagna et al. (1998). In this study a Class I response is observed.

I.IV Seismic Rock-Properties in Relation to Seismic Data and AVO

In this study, a class I is depicted in the carbonate play.
Such a reduction in $V_P$ is not commonly seen in gas-filled porous limestones because their porosity is usually different from, and less compressible than that of sandstone pore structures (Chopra & Castagna, 2014). As a result, it is often believed AVO is not useful in well-lithified carbonates.

\begin{equation}
V_p \left( \frac{m}{s} \right) = \sqrt{\kappa + \frac{4}{3} \frac{\mu}{\rho}}; \quad V_s \left( \frac{m}{s} \right) = \sqrt{\frac{\mu}{\rho}}
\end{equation}

Where $\rho = \text{density \ (g/cm}^3\text{)}$; $\mu = \text{shear modulus}$; $\kappa = \text{bulk modulus}$

I.V Pre-stack Inversion

Seismic inversion assists in oil and gas exploration by converting reflection data into quantitative data representing the rock properties present within the subsurface. Post-stack inversion essentially transforms the seismic amplitudes into p-wave acoustic impedance (which lacks the low-frequency component), yielding potentially inaccurate results (Chopra & Castagna, 2014). However, in pre-stack inversion, both the low- and high-frequency components of the p-wave acoustic impedance can be extracted from the seismic data (Mallick and Ng, 1995). Pre-stack inversion is done using sonic, density and shear wave logs, along with offset or angle dependent gathers to calculate the p-impedance, s-impedance, and a $V_p/V_s$ ratio which provides fluid estimation for the reservoir; thus, pre-stack inversion has an advantage of post-stack inversion (Chopra & Castagna, 2014). In this study, an elastic impedance inversion was completed for the angle ranges of 10 – 30 degrees. A typical inversion flowchart is shown in figure 9.
As mentioned above, a drop in Poisson’s ratio may indicate the presence of natural gas in the subsurface. The $V_p/V_s$ ratio is directly correlated to poisson’s ratio as shown in equation 1.2 below. Thus, a drop in the $V_p/V_s$ ratio corresponds with a drop in Poisson’s ratio, indicating the possible presence of hydrocarbons. Pre-stack inversion, combined with AVO analysis, yields important information regarding rock properties that pertain to the presence of hydrocarbon-filled facies within the subsurface.

\[
\sigma(PR) = \frac{1}{2} \left( \frac{V_p^2 - 2V_s^2}{V_p^2 - V_s^2} \right);
\]

\textit{Where} $V_p = p – \text{wave velocity} \left( \frac{m}{s} \right)$, $V_s = s – \text{wave velocity} \left( \frac{m}{s} \right)$

Figure 9: Typical inversion flowchart, from petrologic.dmt.de
I.VI Previous Research

Past research done on AVO in carbonates has revealed ambiguous results. Li et al. (2003) recognized that fluid does affect carbonate rock properties and with significant magnitude. Their study concludes, from theoretical models, that a wet porous limestone encased in tight limestone yields a similar response to a porous dolomite encased in tight limestone which they determine as a Class III AVO response. Eissa et al. (2003) was also able to identify a dolomitic gas-producing zone versus a tight limestone by the presence of a strong-negative gradient on the tight limestone versus a low-positive gradient on a gas-producing dolomite. However, Isaac and Lawton (2009) attempted to use AVO analysis in data from the Redwater reef, Alberta area to distinguish porous dolomitic zones encased in limestone, from tight limestone and were unsuccessful. These results display the uncertainty present in previous carbonate AVO research.

Despite the majority of large oil-producing fields being carbonate reservoirs, AVO in carbonates is not well researched and should be completed in individual basins to determine the possibility of using these methods for future hydrocarbon detection. The lack of sonic and density logs throughout the Illinois Basin makes it impossible to analyze certain fields using pre-stack inversion and AVO analysis. Because of this, it would be useful to obtain modern sonic, shear-wave, and density logs in areas where they are not available.
II. METHODS

II.I Data Preprocessing

Seismic data were donated by CountryMark and were preprocessed into Ostrander CMP (common mid-point) gathers with the primary purpose of enhancing the signal-to-noise ratio. Ostrander gathers are generated from supergathers by stacking traces with similar offset intervals (Xu and Chopra, 2007). Usually, the individual traces within a CMP (common mid-point) gather have a poor signal-to-noise ratio (S/N). By choosing a group of CMPs and a shot-to-group offset range, a partially summed gather can be generated that displays an improved S/N and enhances the AVO effect (Chopra & Castagna, 2014). The most important step when processing and conditioning seismic data for pre-stack interpretation is to preserve the true signal amplitudes. This means data conditioning must be done carefully in order to achieve unbiased results. The conditioning parameters for each process were chosen to ensure data was not altered by comparing gathers for each conditioning step to the preceding gathers.

II.II Old Hill-CM-46-12

Due to the difference in data quality of each of the lines in the study, each line was conditioned slightly different than the other. The goal was the same, to produce amplitude compliant volumes to detect the presence of hydrocarbons in each locality.
Using Hampson-Russell software, a parabolic radon filter was applied to remove random noise and multiples. Figure 10 shows the data with raw gathers, radon filtered gathers, and the noise removed throughout the process.

The parameters for this radon filter were $\text{low delta } T = -10 \text{ ms}, \text{ high delta } T = 50 \text{ ms}$, with a noise/signal ratio of .2. Following the application of a radon filter, a trim static was applied to the NVL interval to correct residual moveout. The trim static had a maximum time shift of 5 milliseconds and a cross-correlation window of 20 milliseconds. CMP offset gathers were converted into incident angle gathers using the RMS velocity field. The angles ranged between 10 – 30 degrees, due to the lack of coverage at near and far offsets. These gathers were used to create AVO intercept and gradient volumes.

![Figure 10: Shows the area of interest (red) where the strong positive reflector is the North Vernon Limestone (~310 ms). Data from Old Hill Field (CM-46-12).]
IHS Kingdom seismic interpretation software was used to interpret the AVO response from conditioned CDP gathers. Intercept and gradient attribute volumes were then created using a two-term Shuey analysis due to its validity for incident angles less than 35 degrees. The Shuey approximation is shown in equation 2.1 (Shuey, 1985).

The gathers were examined individually at each well location using an amplitude versus angle cross plot, which was used to determine the response from productive versus nonproductive North Vernon Limestone.

\[
R(\theta) = R_0 + \left[ A_0 R_0 + \frac{\Delta \sigma}{(1-\sigma)^2} \right] \sin^2(\theta); \text{ where } R_0 = \text{normal incidence p-wave reflectivity, } \sigma = \text{Poisson's ratio, } A_0 = \text{Amplitude, and } \theta = \text{angle of incidence (0 – 30 degrees)}
\]

Old Hill was chosen because it was the first data set made available that had well control and a history of production. Full-offset synthetic models were developed to validate the in-situ response observed on the field data using well logs provided by the Indiana Geological and Water Survey (IGWS).

As no shear-wave logs are available, we created a shear-wave log using a compressional log from the well “Rentschler 1-54773” and a \( V_p/V_s \) relationship of 2. The wet (i.e. brine) model was created by modifying Poisson’s ratio to be 0.33, whereas the gas model was created by modifying Poisson’s ratio to be 0.20. These models were then tied to their respective well locations on the seismic data.
II.III Glen Ayr-CM-27-14

The conditioning steps for this seismic line differed slightly from the Old Hill seismic line. A bandpass filter was run on the Ostrander CMP gathers with parameters 5hz-10hz-90hz-120hz (low cut-low pass- high pass- high cut). A bandpass filter removes both low frequency (ground roll) and high frequency (ambient noise) from the data and leaves the reflection character behind (Yilmaz, 2001). Frequencies below the low cut and above the high cut are removed from the data.

Following the application of a bandpass filter, a trim static was applied to correct for residual moveout error, with the NVL as the target interval. The max time shift for the trim static was 7 milliseconds, with a cross-correlation window of 20 milliseconds. A radon filter was applied to remove multiples and random noise from the data, with parameters of low delta T = -5ms, high delta T = 25ms, with a noise/signal ratio of .5. Finally, another trim-static was applied to the data to flatten the NVL interval with a maximum time shift of 5 milliseconds, and a cross-correlation window of 15 milliseconds. Figure 11 shows the bandpass filtered gather, along with the final gather and the noise removed. As you can see, the radon filter did not remove any coherent reflections from the data. The CMP gather was converted into incident angle gathers using the stacking velocities created from principle time processing of the data. AVO gradient and intercept volumes were generated from these gathers using a two-term Shuey approximation.
Along with the AVO volumes, a model based elastic impedance inversion was done using the angle gathers. A sonic and density log from the well “Hulman Farm 8-166206” were obtained from the IGWS. A shear-wave log was calculated using Castagna’s equation (Eq. 2.2) (Castagna et al, 1993). These three logs (Figure 12), along with an extracted statistical wavelet, were utilized to create the initial inversion model. In this method, the seismic trace (initial model) is convolved with a wavelet to get a synthetic seismic trace. Many iterations of the inversion are performed until the difference between the inverted trace and the initial trace is reduced to a limit value (Veekan, 2004).

The final inversion allows for the quantitative determination of p and s-impedance, as well as $V_p/V_s$ ratio, which can relate to Poisson’s ratio. The pre-stack inversion, combined with the AVO interpretation, allow for the determination of hydrocarbon-bearing zones.
\[ V_s \left( \frac{m}{s} \right) = a \times V_p \left( \frac{m}{s} \right) + b; \]

where \( a = 0.8616, b = -1172 \) and \( V_p = p\text{-wave velocity} \)

Figure 12: Shows the Sonic, Shear-wave (calculated), and density logs used to perform AVO analysis along with the elastic pre-stack seismic inversion on line CM-27-14. The NAS and NVL tops are denoted.
III. RESULTS

III.I Old Hill-CM-46-12

The stacked seismic section (Figure 6) shows no definitive amplitude response generated by the presence of hydrocarbons, despite the producing wells in the area. However, a pre-stack seismic AVO response is observed and displayed in Figure 13. The AVO gradient volume shows a strong, negative gradient present along the NVL interval that correlate well to hydrocarbon producers. The AVO volume was used as a scout volume to identify zones to study via amplitude versus angle cross plot analysis. The gathers, shown in Figure 14, show a definitive negative gradient present in pay zones, whereas the dry-hole response appears to display a positive gradient.

In order to confirm the in-situ response, a synthetic model was generated using a “wet-non producer response” versus a “producer response” with different Vp/Vs ratios. This model is shown in Figure 15. The model predicts a strong negative gradient present along the NVL interval when the facies is hydrocarbon-filled versus no gradient when the NVL is brine-filled or dry.
Figure 13: Shows the AVO gradient volume generated on seismic line CM-46-12 (Clay). A definitive amplitude response is observed along the NVL interval. The dry hole “Rentschler 1 (B)” appears to fall into a positive gradient, the only well to do so.

Figure 14: Shows the gathers for seismic line CM-46-12 (Clay) on the dry hole (left), producer (middle) and injection well (right). It is important to note the injection well had a show of oil. The wells that contained hydrocarbons display a strong negative gradient whereas the dry hole has a positive gradient.
Figure 15: Shows the synthetic model derived for CM-46-12 (Clay). The wet model (left) with a Poisson’s Ratio of .33 shows no gradient, whereas the gas model (right) with a PR of .2 shows a strong negative gradient.
III.II Glen Ayr-CM-27-14

Although the conventional stacked section (Figure 7) shows no definitive amplitude response generated by the presence of hydrocarbons, a pre-stack response in the NVL interval generated by the presence of hydrocarbons is observed on seismic line CM-27-14 in the Glen Ayr oil field. The synthetic tie, along with the stratigraphic picks are shown in Figure 16.

Figure 16: A simplified stratigraphic column created using sonic and gamma logs obtained from the Hulman Farm 8 well (IGS ID 166206) and seismic line CM-27-14 outlining the formations of interest. The sonic log velocity scale is 5,000 ft/s – 20,000 ft/s (1,524 m/s – 6,096 m/s). The gamma-ray log scale is 0 – 300 API units. The North-Vernon Limestone (NVL), New-Albany Shale (NAS), and the Borden Group (Borden GP) are picked and tied to their respective locations on the analog
The AVO gradient volume generated from the pre-stack seismic shows a strong negative gradient present in areas along the NVL interval; these zones are shown in colors ranging from green to red in Figure 17. The gradient volume was used as a scout volume to locate anomalous zones possessing this negative gradient for further analysis. From this volume, gathers containing productive and nonproductive zones known from well control were compared to observe their response (Zones 1-4). We observe a strong negative gradient on the NVL peak (sometimes in trough below depending on the location of hydrocarbon-based porosity) in productive zones (Figure 18 pay zone), whereas dry zones exhibit a positive gradient along the NVL (Figure 18 no pay zone). The position of the gradient is relative to the location of the porosity caused by the presence of gas-filled facies.

To support our AVO analyses, a pre-stack impedance inversion was done to strip the wavelet from the reflection data, leaving behind quantitative rock properties. The inversion shows high-impedance zones (49,000 – 51,000 [ft/s * g/cc]) outlined in black in Figure 19. These high impedance zones suggest the presence of a tight, low-porosity carbonate seal overlying the productive zones within the NVL interval. Lower impedance zones (42,000 – 44,000 [ft/s * g/cc]) are observed below the top of the structure along with a $V_p/V_s$ of 1.55 and strong negative AVO gradient, which may indicate the presence of hydrocarbon-bearing dolomite on structure.
The high impedance zones on the flank of the structure suggest a thicker, tight carbonate interval with low porosity (zone 3), whereas on structure the tight carbonate has thinned and has higher porosity (zone 2). Off the flank of the structure zones 1 and 2 represent areas with lower impedance (44,000) and low Vp/Vs (1.55) ratios as well that are producers. Further analysis is suggested to validate this response as it would be useful to obtain cores from both productive and nonproductive zones; thus, allowing for seismic velocities to be extracted directly from the cores.

Figure 17: AVO gradient volume from line CM-27-14, with zones of interest (black). Negative gradients (red - green zones) may correspond to the presence of hydrocarbons. These zones were examined by amplitude versus angle crossplot analysis.
Figure 18: Nonproductive gather (CDP 266), and productive gather (CDP 415) showing strong negative gradient present on the NVL peak on line CM-27-14. The nonproductive gather displays a positive gradient along the NVL peak.

Figure 19: Pre-stack impedance inversion of line CM-27-14 showing anomalous high-impedance zones (purple) outlined in black within the zone of interest. Zone 3 may correspond to tight, low porosity carbonates, whereas zone 4 looks to have a thinner tight interval along structure, with a lower impedance. This suggests a higher porosity zone, along with the lower impedance zones off the structure (1 and 2).
Figure 20: Inverted $V_p/V_s$ ratio along the NVL interval on line CM-27-14. Areas with low impedance values have $V_p/V_s$ values between 1.55 and 1.6, which is expected in a porous carbonate. Hydrocarbon-bearing zones are differentiated from brine-filled zones by $p$-impedance value, along with the presence of a strong negative AVO gradient.
IV. DISCUSSION

IV.I Interpretation of Results

The pre-stack interpretation methods used in this study show a definitive seismic response caused by the presence of hydrocarbons, or direct hydrocarbon indicators. Zones containing hydrocarbon-filled porosity in both Old Hill and Glen Ayr oil fields display anomalous negative gradients on the AVO volume unlike the typical lithologic response generated along the NVL interval. Amplitude versus angle cross plotting on individual gathers shows a definitive Class 1 AVO response generated in areas known to be producers from well control, whereas dry holes exhibit a positive or no gradient. On seismic line CM-46-12, the synthetic model agrees with the in-situ response displaying a strong negative gradient when gas is present (PR = .2). The wet model (PR = .33) shows no gradient along the interval confirming our analyzes of the in-situ response when no hydrocarbons are present.

The pre-stack inversion on seismic line CM-27-14 confirms the presence of a tight carbonate seal overlying the productive reef complex. The productive dolomite is shown on the inversion as anomalous low impedance, low $V_p/V_s$ ratio zones within the NVL interval, whereas off the flank of the structure high impedance zones may represent tight, low porosity intervals.
Our analysis suggests that using AVO attributes and pre-stack inversion in combination can detect the presence of hydrocarbon-based porosity in carbonate rocks. Pre-stack data offers valuable information regarding seismic rock properties that is commonly lost in stacked data; however, the application of pre-stack methods offers potential for the discovery of new economic oil reservoirs in the Illinois Basin.

**IV.II Industry Implications**

The wells drilled over reef-drape complexes in this area were primarily located based on structural highs caused by the presence of these features. However, using pre-stack interpretation methods, hydrocarbon-bearing zones that are trapped off structure are also observed. This advanced interpretation method may prove useful in exploration of existing fields in areas previously thought to be unpromising. Also, new prospects may be developed in areas with less distinct structure being evident.

Pre-stack seismic interpretation provides a company with valuable information pertaining to the seismic rock properties that are unavailable in the post-stack seismic data. The pre-stack data is often never considered or analyzed when drilling in this area despite the data already being present. From this study, it is clear that pre-stack seismic interpretation provides information that can be used in conjunction with stacked data to determine the best possible drilling prospects while avoiding unnecessary dry holes.

**IV.III Possible Caveats**

Although the seismic data was processed and conditioned carefully, it is important to recognize the possibility of over-conditioning of data or vice versa. Since the target zone is relatively shallow (~1500 feet or 450 meters), the data contains high-frequency ambient noise that may affect seismic amplitudes. Data conditioning may also create
false-positive anomalies. However, careful processing and comparison of each step in the
data conditioning in this study lessens the chance of ambiguity in the data.

Another source of error in this study is associated with the calculation of the shear-
wave log used in the inversion process. Castagna’s mudrock equation was used to
calculate the shear wave log and is a well-accepted method in many basins throughout the
world. However, the equation was derived from siliciclastic mudrocks that have many
dissimilarities to the carbonates in this study. In order to reduce ambiguity in the shear-
wave calculation, an inversion was ran using Castagna’s dolomitic equation (Castagna et
al. 1993) (eq. 4.1.) and the results were deemed inconclusive due to erroneous calculation
of the rock properties, so the mudrock equation was used.

\[
(4.1) \quad V_s \left( \frac{m}{s} \right) = 0.583 V_p \left( \frac{m}{s} \right) - 0.078
\]
V. Conclusions

V.I. Summary

The purpose of this study was to determine if pre-stack seismic interpretation methods such as inversion and AVO analysis can detect the presence of hydrocarbons in well-lithified midcontinent carbonate rocks. The results show the presence of a definitive amplitude response present within the target interval of both seismic line CM-46-12 in Clay County, Indiana and seismic line CM-27-14 in Vigo County, Indiana constrained and confirmed by well-control. In the Old Hill oil field (CM-46-12) a synthetic model verified the in-situ response seen on the gathers and confirmed the presence of a class I AVO response corresponding to hydrocarbons along the North Vernon Limestone interval.

The Glen Ayr oil field line (CM-27-14) displayed a Class I AVO response along the NVL interval similar to what was observed in the Old Hill oil field. A pre-stack impedance inversion was done on seismic line CM-27-14 to assist in exploration and confirmed the presence of tight, high-impedance, low-porosity zones along the flank of the reef structure. Zones displaying lower-impedance, low Vp/Vs ratios in conjunction with negative amplitude gradients correlate well to known hydrocarbon producing wells in the area. The results of this study suggest that pre-stack seismic methods are useful even in well-lithified carbonates to identify hydrocarbon prospects.
V.II Future Work

Although the vast majority of oil and gas reservoirs occur in carbonates, not much research has been completed on the use of pre-stack seismic methodology in these rocks; specifically, the use of pre-stack seismic data in midcontinent, well-lithified carbonates. To better understand the seismic response associated with midcontinent carbonates, studies should be done over large onshore oil fields. It would be useful to obtain sonic, shear-wave, and density logs in hydrocarbon-saturated carbonates, brine-saturated carbonates, and dry carbonates onshore to better understand how their porosity and fluid content alter the pre-stack seismic response in these rocks.
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